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BALLISTIC DAMAGE CHARACTERISTICS AND FRACTURE TOUGHNESS OF LAMI--ETC(U)
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BALLISTIC DAMAGE CHARACTERISTICS AND FRACTURE TOUGHNESS OF LAMINATED ALUMINUM 7049-T73 AND TITANIUM 6Al-4V ALLOYS

CHARLES F. HICKEY, Jr., and ALBERT A. ANCTIL
METALS RESEARCH DIVISION

March 1980

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ABSTRACT

The purpose of this research study was to define the degradation of metal laminate structural properties resulting from damage by 12.7-mm API projectiles fired at 1600 feet per second. Materials investigated were Al-7049 and Ti-6Al-4V laminates ranging from 0.100 to 0.400 inch in nominal thickness. Data to be presented and discussed include fracture toughness (K_Q and W/A) as a function of laminate thickness, plus a characterization of the ballistic damage and residual strength of the various laminates.

Results indicate that laminate thickness over the range studied has little or no effect on the fracture toughness of either Al-7049 or Ti-6Al-4V. The ballistic penetration mechanism for both alloys was by petalling and in general the damage increased as a function of laminate thickness.

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A

INTRODUCTION

In past transport helicopter designs, available space has been the overriding design constraint for about 50% of the components. Strength-to-volume is often just as important as strength-to-weight. Based on history, the ballistic threats faced by a helicopter fleet during its service life can be expected to increase. Available space and ballistic threat growth generate the requirement to provide survivability to larger threats in the same volume or space filled by components that were designed to be survivable against a lower-order threat. Since 50% of the original designs were space/volume limited, this requirement can be a rigorous design challenge. Laminated sheet metal promises to reduce and, in many cases, eliminate much of the cost/time problems in upgrading survivability in existing fleets and to reduce the cost of the components redesigned in laminates as well.[1]

Some significant findings related to metal laminates are as follows.

1. The service temperature range over which fully ductile fracture can be obtained under impact loading is lower for metals in laminate form than in the monolithic form.[2]

2. Impact energy enhancement for mild steel can be obtained in laminated versus monolithic form when using either a crack arrester or crack divider oriented specimen.[3]

3. In high-strength dual hardness steels the impact energy of longitudinally oriented crack divider and crack arrester specimens is higher over the test temperature range of -196 C to +180 C. Fracture toughness, as measured by K_Q (using precracked Charpy V-notch specimens), shows the same trend except for the crack arrester specimens precracked on the hard side. K_Q values for the hard side are relatively unaffected by orientation or test temperature.[4]

4. Laminated aluminum sheet metal structures have a small weight advantage over forgings despite the added weight of adhesive.[5] The higher static mechanical properties of sheet aluminum, compared to forgings, was sufficient to offset the weight of adhesive.

1. DEGNAN, W. G., HICKEY, C. F., Jr., and ANCTIL, A. A. *Improved Ballistic Damage Tolerant Design Through Laminated Metal Construction.* Presented at the American Helicopter Society Meeting, November 1977, NASA-Ames, Moffett Field, California.
2. ARNOLD, S. V. *Toughness of Steel Sheet: The Advantage of Laminating.* Army Materials and Mechanics Research Center, WAL TR 834.21/2, October 1960.
3. ALMOND, E. A., EMBURY, J. D., and WRIGHT, E. S. *Fracture in Metal Laminates.* ASTM STP 452, 1969.
4. LUM, P. T., CHAIT, R., and HICKEY, C. F., Jr. *The Toughness of High Hardness Laminar Composite Steel as Influenced by Specimen and Crack Orientation.* AIME Metallurgical Transactions, v. 6A, May 1975.
5. BAIRD, R. B., FORBES, F. W., and LIPSITT, H. A. *Tensile and Fatigue Properties of Laminated Sheet Structures.* ASTM Proc., v. 59, 1959, pp. 755-756.

5. Numerous subsequent efforts have indicated that the fracture toughness values of metal laminates is equal to or superior to values obtained from the monolithic condition.[6-10]

Research in the area of metal laminates at the Army Materials and Mechanics Research Center (AMMRC) dates back to the late 1950's[2,11] when the Center was known as Watertown Arsenal Laboratories (WAL). Efforts have been continued by various AMMRC associated personnel[12-18] and the most recent work, entitled "Improved Ballistic Damage Tolerant Design Through Laminated Metal Construction",[1] was presented at the American Helicopter Society/NASA-Ames Conference in November 1977. This report describes the AMMRC portion of this cooperative effort with Sikorsky Aircraft.

MATERIALS, LAMINATE FABRICATION, AND TEST PROCEDURE

Materials

The materials explored were the aluminum alloy 7049 in the T-73 condition and the titanium alloy 6Al-4V in the beta solution-treated-plus-overaged condition. Both materials were procured in nominal sheet thicknesses of 0.050, 0.100, 0.200, 0.300, and 0.400 inch by 12 inches square. The Al-7049 was obtained and tested in the T-73 condition. This condition is a company proprietary treatment, however it can be stated that it represents an overaged condition. The Ti-6Al-4V was tested in the following mill heat-treated condition:

6. KAUFMAN, J. G. *Fracture Toughness of 7075-T6 and T-651 Sheet, Plate and Multilayered Adhesive-Bonded Panels.* Quarterly Trans., ASME, Journal of Basic Engineering, v. 89, Series D, September 1967, pp. 503-507.
7. COX, D., and TETELMAN, A. S. *Improved Fracture Toughness of Ti-6Al-4V Through Controlled Diffusion Bonding.* AFML-TR-71-264, February 1972.
8. ELLIS, J. R., and KUHN, G. E. *Adhesively Bonded Multi-Layer F-104 Aft Fuselage Ring Fitting.* AFML-TR-74-158, November 1974.
9. THROOP, T. F., and FRYCZAK, R. R. *A Fracture-Resistant Titanium-Aluminum Laminate.* ASTM Symposium on Toughness and Fracture Behavior of Titanium, ASTM STP 651, 1978.
10. GOOLSBY, R. D. *Fracture and Fatigue of Diffusion, Explosive, and Roll Bonded Al/Al and Ti/Al Laminates.* Vought Corporation, Advanced Technology Center, Dallas, Texas, ATC Report No. B-94400/7CR-23 Contract No. N00010-76-C-0288, 13 May 1977.
11. ARNOLD, S. V. *Notch Sensitivity and Laminated Charpy Impact Strength of 1100-F and 2024-T4 Aluminum Alloy Simulated Sheet.* Army Materials and Mechanics Research Center, WAL TR 341.5/1, September 1959.
12. HICKEY, C. F., Jr. *Mechanical Properties and Bonding Efficiency of Steel Composites.* ASTM Journal of Materials, v. 3, no. 1, March 1968.
13. CHAIT, R., and CURLL, C. H. *Mechanical Behavior of Ballistically Damaged and Undamaged Laminar Composite Armor Steel.* Army Materials and Mechanics Research Center, AMMRC TR 73-59, December 1973.
14. ANCTIL, A. A., CHAIT, R., CURLL, C. H., and KULA, E. B. *Structural Properties of Dual Hardness Steel Armor.* Army Materials and Mechanics Research Center, AMMRC TR 73-6, February 1973.
15. HICKEY, C. F., Jr. *Toughness Data for High Hardness Laminar Composite Steel.* Army Materials and Mechanics Research Center, AMMRC TN 74-4, April 1974.
16. KULA, E. B., ANCTIL, A. A., and JOHNSON, H. H. *Fatigue Crack Growth in Dual-Hardness Steel Armor.* Army Materials and Mechanics Research Center, AMMRC TR 74-6, April 1974.
17. CAMPBELL, M. D., and CHAIT, R. *A Fracture Mechanics Approach to the Residual Strength Behavior of Ballistical Damaged High Hardness Laminar Composite Steel.* J. Engineer Fracture Mechanics, Pergamon Press, v. 8, 1976.
18. ARNOLD, S. V. *Ballistic Behavior of Aluminum Alloy Laminates.* Army Materials and Mechanics Research Center, AMMRC TR 77-24, October 1977.

Solution Treatment	1850 to 1900 F, 15 min, AC
	1725 F, 1 hr, AC
Aging Treatment	1300 F, 1 hr, AC.

The nominal chemical composition for Al-7049 and the composition for Ti-6Al-4V as supplied by the producer, are shown in Table 1.

Table 1. CHEMICAL COMPOSITION

Al 7049*			Ti-6Al-4V+	
	Composition (Wt%)			
Element	Min	Max	Element	Composition (Wt%)
Zn	7.2	8.2	Al	5.8
Mg	2.0	2.9	V	4.1
Cu	1.2	1.9	Fe	0.10
Cr	0.10	0.22	C	0.020
Fe	-	0.35	N	0.010
Si	-	0.25	H	0.008 ppm
Mn	-	0.20	O	0.13
Ti	-	0.10	Ti	Balance
Others	Balance	0.15		

*AMS 4111, "Forging 7.7 Zn-2.5 Mg-1.5 Cu-0.15 Cr", November 1, 1970.
+As provided by producer.

Laminate Fabrication

The adhesive bonding phase of the program was performed by Vought Corporation, Systems Division, Dallas, Texas, under Contract No. DAAG46-76-M-2078.[19]

The laminated panel configuration for both materials is shown in Table 2. The titanium and aluminum 12 inch square panels were assembled in a longitudinal orientation using the M-113 epoxy film adhesive over a BR-127 bond primer. Fabrication and inspection were accomplished using materials, processes, and procedures which are representative of current aerospace practices for metal bonding

Table 2. LAMINATED PANEL CONFIGURATION AND QUANTITY

Nominal Laminate Thickness (in.)	Metal Ply		Number of Panels	
	Nominal Thickness (in.)	Number	Al 7049	Ti-6Al-4V
0.1	0.05	2	4	4
0.2	0.10	2	7	7
	0.05	4	4	4
0.3	0.10	3	8	8
	0.05	6	3	3
0.4	0.20	2	8	8
	0.10	4	7	7
	0.05	8	3	3
	TOTAL		44	44

19. KUHN, G. E., and SHELTON, S. I. *Fabrication of Adhesively Bonded Laminated Metal Panels.* Vought Corporation, Contract No. DAAG46-76-2078, October 1976.

and laminated structural fabrication. The through-transmission ultrasonic technique was used by Vought for nondestructive inspection and they reported that no significant bond flaws or defects were detected in any of the laminated panels. Permanent C-scan recordings were made for each panel.

Test Procedure

The program was modified to address the laminate thicknesses cited in Table 3. Areas to be investigated are as follows: (1) ballistic damage characterization after impact with 12.7-mm API projectiles, (2) residual strength determination, and (3) fracture toughness data from undamaged panels.

Table 3. LAMINATED PANEL CONFIGURATION AND QUANTITY

Nominal Laminate Thickness (in.)	Ply		Number of Panels	
	Nominal Thickness (in.)	Number	Al 7049	Ti-6Al-4V
0.1	0.05	2	4	4
0.2	0.05	4	4	4
0.3	0.05	6	3	3
0.4	0.05	8	3	3

One panel of each laminate thickness for both materials was subjected to two ballistic impacts at locations shown in Figure 1. The ballistic design threat of the Army's advanced helicopter, 12.7-mm API at a velocity of 1600 fps, was selected. The panels were then cut in half, and thus two 6x12 inch panels per laminate thickness were available for residual strength studies. Photographs were taken of all ballistically impacted entrance and exit regions.

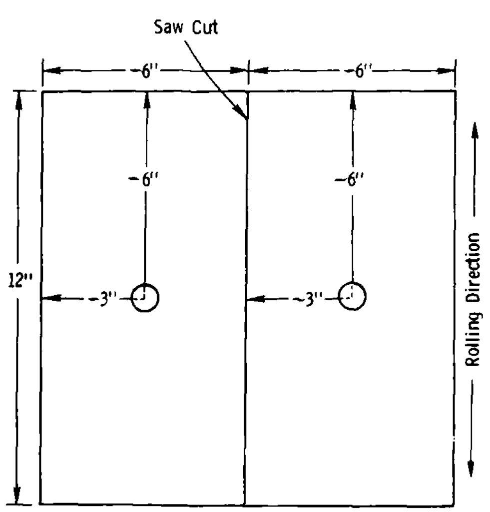

Figure 1. Typical laminated panel.

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Key Words

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Titanium alloys
Aluminum alloys

Monograph Series AMMRC MS 80-1, March 1980, 22 pp - illus-tables, D/A Project 1L162105AH84, AMCMS Code 612105H84

The purpose of this research study was to define the degradation of metal laminate structural properties resulting from damage by 12.7-mm API projectiles fired at 1600 feet per second. Materials investigated were Al-7049 and Ti-6Al-4V laminates ranging from 0.100 to 0.400 inch in nominal thickness. Data to be presented and discussed include fracture toughness (K_Q and W/A) as a function of laminate thickness, plus a characterization of the ballistic damage and residual strength of the various laminates. Results indicate that laminate thickness over the range studied has little or no effect on the fracture toughness of either Al-7049 or Ti-6Al-4V. The ballistic penetration mechanism for both alloys was by petalling and in general the damage increased as a function of laminate thickness.

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Dog-bone tension specimens were machined from each of the 6x12 inch panels. The tensile axis was parallel to the major rolling direction of the material. Residual strength data were obtained from these specimens utilizing a 150,000-lb hydraulic closed-loop testing machine. The residual strength was calculated from the breaking load and the net cross-sectional area remaining after ballistic penetration. The net cross-sectional area, measured after fracture, was the summation of the average length times the thickness (material which supported the applied load) of each ply making up the laminate.

Fracture toughness data (K_Q and W/A) were obtained from each laminate using a slow-bend type specimen as shown in Figure 2. Specimens were machined in a longitudinal orientation with the crack running in the transverse direction, which constitutes a crack-divider configuration. The specimens were precracked approximately 0.080 inch on an SF-1U Sonntag machine and then loaded to fracture on a Physmet slow bend machine. K_Q is a conditional plane strain fracture toughness (K_{Ic}) value and W/A is obtained by dividing the breaking energy by the specimen area (including adhesive) beneath the fatigue crack.

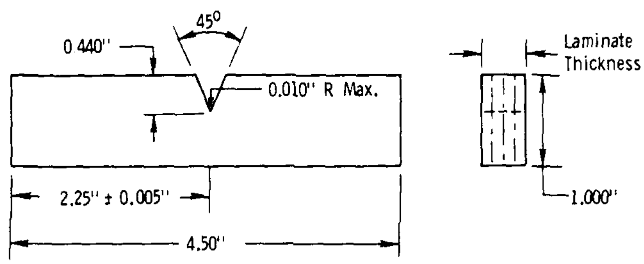


Figure 2. Slow-bend fracture toughness specimen.

RESULTS AND DISCUSSION

Data which will be presented are fracture toughness (K_Q and W/A) for the aluminum and titanium alloy as a function of actual laminate thickness, plus a characterization of the ballistic damage and residual strength of the various laminates. Photographs of the fracture surface of the fracture toughness specimens and of the ballistically impacted areas, both entrance and exit regions, will also be shown and discussed.

Fracture Toughness

Fracture toughness data for the Al-7049 are shown in Table 4. Although the magnitude may not be great, there is an increasing trend in K_Q and W/A data as a function of laminate thickness. Respective values as a function of laminate thickness are 42.2, 46.0, 46.3, and 47.8 ksi $\sqrt{\text{in.}}$, and 887, 1031, 1052, and 1028 in.-lb/in.^{2}. This trend is similar to data obtained for 0.063-in. plies of 7075-T6 aluminum in which the plane strain stress intensity factors of multilayered adhesive bonded panels are independent of the thickness and number of plies making up the panel.[5] Figure 3a shows typical fracture surfaces for each laminate thickness. The fracture is full shear, alternating from one surface to the other, indicating

Table 4. FRACTURE TOUGHNESS OF Al-7049 IN VARIOUS LAMINATE THICKNESS

Laminate Thickness (in.)	No. of Plies	K_Q ksi $\sqrt{in.}$	W/A in.-lb/in.^{2}
0.109	2	44.4	826
0.111	2	40.1	867
0.109	2	44.2	968
		42.2	887
0.227	4	45.2	1029
0.230	4	47.1	1043
0.225	4	45.6	1041
0.225	4	46.1	1010
		46.0	1031
0.339	6	46.4	1045
0.346	6	46.1	1063
0.335	6	46.3	1048
		46.3	1052
0.453	8	48.0	1024
0.453	8	47.6	1032
		47.8	1028

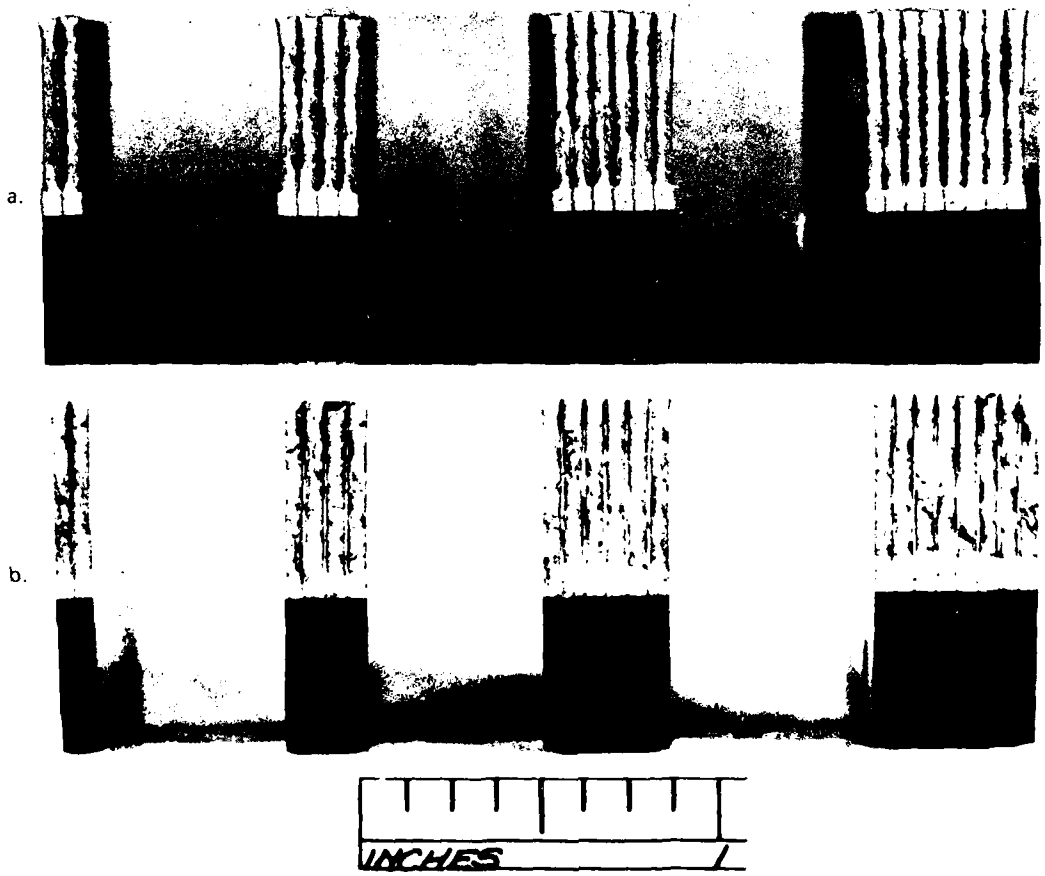


Figure 3. Fracture surfaces from laminated (a) aluminum 7049-T73 and (b) titanium 6Al-4V.

good plane stress fracture toughness. Delamination occurred in the immediate area of the fracture with the epoxy adhering to each ply surface.

Fracture toughness data for the Ti-6Al-4V as a function of laminate thickness is shown in Table 5. Respective K_Q and W/A values for the four laminates are 77.9, 79.7, 70.0, and 75.6 ksi $\sqrt{in.}$, and 930, 956, 765, and 866 in.-lb/in.^{2}. In general, one may conclude that laminate thickness has no apparent effect on the investigated toughness parameters. Maximum values were obtained from the 4-ply structure and minimum from the 6-ply structure. The fracture surface for each laminate thickness is shown in Figure 3b. The appearance ranges from shear to flat-type fracture at various locations from the notch for all plies of the four laminates. The adhesive layer remained intact by separating from one of the ply surfaces, thus indicating limited load transfer by shear.

Table 5. FRACTURE TOUGHNESS OF Ti-6Al-4V IN VARIOUS LAMINATE THICKNESS

Laminate Thickness, (in.)	No. of Plies	K_Q ksi $\sqrt{in.}$	W/A in.-lb/in.^{2}
0.104	2	80.3	887
0.105	2	80.5	1077
0.106	2	72.9	825
		77.9	930
0.231	4	71.6	872
0.229	4	81.8	1037
0.231	4	79.0	951
0.231	4	86.3	965
		79.7	956
0.337	6	71.8	764
0.355	6	68.1	765
		70.0	765
0.450	8	72.1	859
0.460	8	75.2	856
0.457	8	79.9	883
		75.6	866

Characterization of Ballistic Damage and Residual Strength

The aluminum and titanium laminate thicknesses (including adhesive) and the ballistic impact velocity from a 12.7-mm API projectile are given in Table 6. The number of cracks and the average crack length resulting from ballistic impact on the entrance and exit plies are given. Crack lengths were measured radially from the center of the ballistic impact. The radial cracks about the entrance hole increased with laminate thickness (number of plies) in the aluminum but remained the same in the titanium alloy.

Aluminum 7049-T73

The ballistic penetration mechanism for each ply/laminate was by petalling. The extent of petalling in the aluminum went from zero, where the petals were wiped off leaving a blunt base, to the formation of cracks (petal type) 1.6 inches long from the center of ballistic impact. As shown in Figure 4, five petals are generally formed and all in the same orientations relative to the major rolling direction. The maximum lateral damage, MLD, is defined as the damage projected to or

Table 6. CRACK LENGTH MEASUREMENTS RESULTING FROM 12.7-MM API BALLISTIC DAMAGE

Aluminum 7049-T73 Laminate Thickness (in.)	Spec. I.D.	Projectile Velocity fps	Entrance Hole No. of Cracks	Entrance Hole Avg. Crack Length (in.)	Exit Hole No. of Cracks	Exit Hole Avg. Crack Length (in.)	Max Lateral Damage (in.)
0.112	A151	1667	3	0.35	0	*	0.80*
0.113	A151	1612	4	0.31	0	*	0.75*
0.225	A251	1585	1	0.40	5	0.72	1.17
0.231	A251	1633	1	0.40	6	0.67	1.28
0.339	A351	1586	4	0.70	5	1.36	2.12
0.346	A351	1631	3	0.47	5	1.33	2.58
0.403	A451	1609	4	0.70	5	1.20	2.12
0.406	A451	1623	6	0.67	4	1.60	3.05
Titanium 6Al-4 V							
0.112	T151	1588	4	0.46	4	0.65	1.28
0.110	T151	1640	4	0.48	4	0.63	1.26
0.232	T251	1589	5	0.57	5	1.10	2.00
0.226	T251	1608	5	0.59	5	0.97	2.25
0.363	T351	1622	4	0.46	4	1.03	1.88
0.348	T351	1661	4	0.48	4	1.12	2.22
0.483	T451	1613	5	0.42	4	1.17	2.22
0.468	T451	1625	4	0.39	4	1.12	2.25

Cracks measured from center of impact.
*No cracking; blunt deformation.

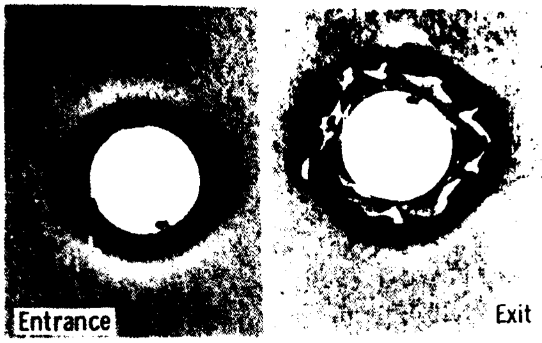
transverse to the applied load. The MLD on the projectile exit face went from 0.8 inch for two plies to a high of 3.0 inches in eight plies. The MLD compared favorably with the upper limit reported by Burch and Avery for monolithic 7075-T6 at thicknesses of 0.125 and 0.375 inch.[20] The MLD for a 0.225-inch laminate was 1.3 inches compared to the MLD for monolithic 7075 at 0.250-inch thickness which measured 3.0 inches.

Figure 5 shows the lateral damage increase as the projectile passes through the laminate. The lateral damage of the 0.2-inch laminate is an extension of the damage to 0.1-inch laminate. Damage increases markedly for all plies when the laminate thickness increases to 0.3 inch. Petal height in turn increases with lateral damage from 0.4 inch (2-ply) to 1.2 inch (6-ply). The greatest amount of delamination occurred in the six-ply laminate, primarily between the entrance and the second ply.

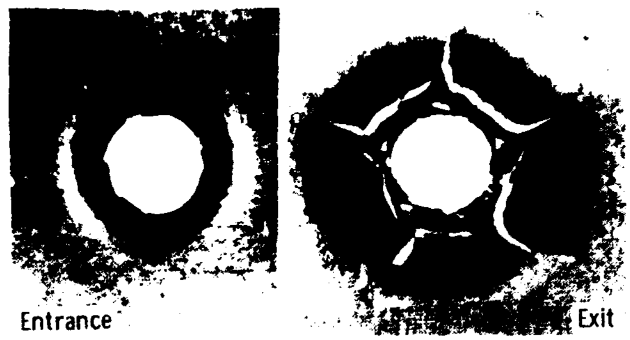
Titanium 6Al-4V

The average crack length and MLD beyond the 2 ply-laminate remained essentially the same (Table 6). The titanium formed four petals (five in T251) with cracks in all cases aligned with and 90° to the rolling direction as shown in Figure 6. An MLD comparison was made of the laminates outer ply with the upper limit of the Burch and Avery data for monolithic Ti-6Al-4V of approximately the same thickness. The results showed significantly less damage for the two-ply laminate, 1.3 inches as compared to 3.6 inches for 0.125-in. monolithic material.

20. BURCH, G. T., and AVERY, J. G. *An Aircraft Structural Combat Damage Model.* Vols. I-III, and Design Handbook, AFFDL-TR-70-115A, B, C, and 116, November 1970.



a. Laminate thickness 0.1 in. - Impact velocity 1667 fps.



b. Laminate thickness 0.2 in. - Impact velocity 1585 fps.

c. Laminate thickness 0.3 in. - Impact velocity 1586 fps.

d. Laminate thickness 0.4 in. - Impact velocity 1609 fps.

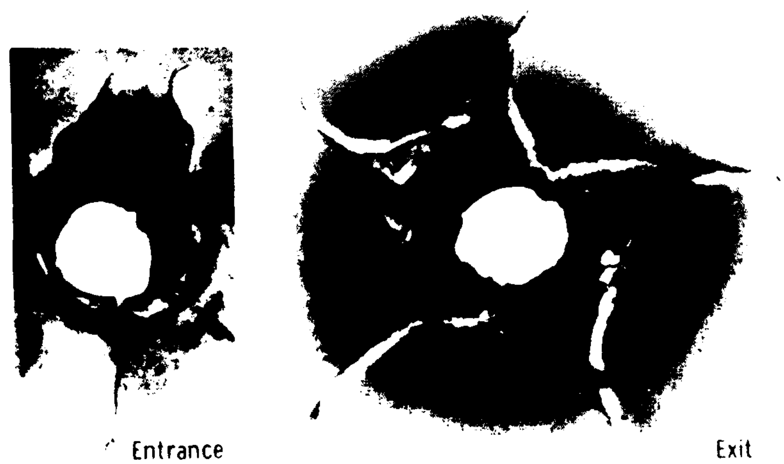


Figure 4. Laminated aluminum 7049-T73 panels ballistically impacted with 12.7-mm API.

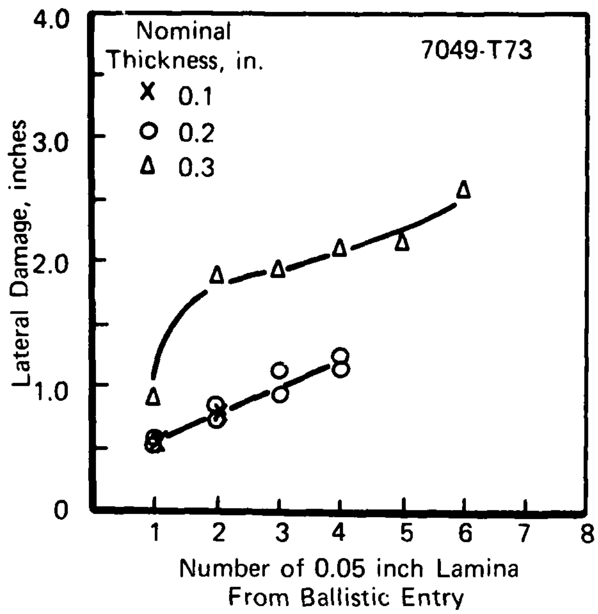


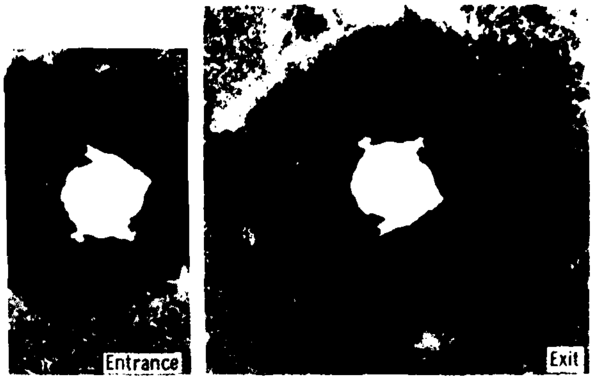
Figure 5. Lateral damage versus number of laminae from projectile entry for aluminum 7049-T73.

The MLD in the four-six-, and eight-ply laminates exceeded the upper limit for corresponding monolithic thicknesses of 0.250, 0.375 and 0.5000 inch.

Residual Strength

The residual strengths for several laminate thicknesses are given in Table 7. Data for all laminate thicknesses were not obtained due to specimen pinhole failures. The residual strength for both alloys decreases with laminate thickness and degree of ballistic damage. It is significant to note that the residual strength of all investigated laminate thicknesses of the aluminum is above the yield strength (65 to 70 ksi) of the material in the monolithic form. For the titanium laminates the two-ply structure failed above its yield strength. Additional work is being conducted to complete the research on the effect of the number of plies on residual strength.

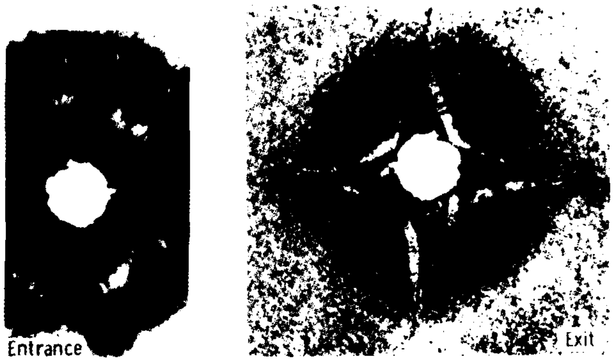
Burch and Avery data for comparable thicknesses of monolithic 7075-T6 indicate a residual strength equal to or considerably less than the yield strength of the material. The two titanium alloy laminates reflect a higher residual strength than that shown by Burch and Avery with the two-ply structure being considerably higher. The titanium alloy residual strength values exceeds that of the aluminum alloy and is in agreement with the tensile strength and fracture toughness values obtained.



a. Laminate thickness 0.1 in. - Impact velocity 1588 fps.

b. Laminate thickness 0.2 in. - Impact velocity 1608 fps.

c. Laminate thickness 0.3 in. - Impact velocity 1661 fps.



d. Laminate thickness 0.4 in. - Impact velocity 1625 fps.

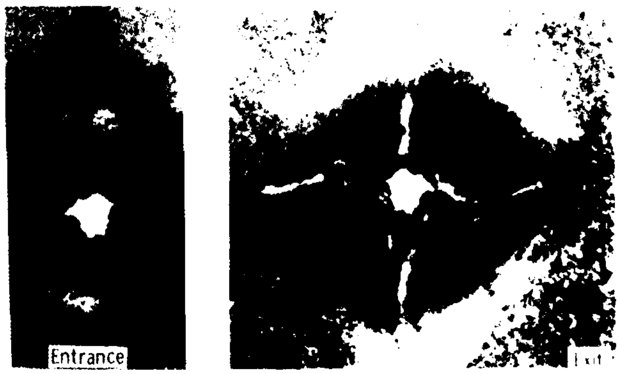


Figure 6. Laminated Ti-6Al-4V panels ballistically impacted with 12.7 mm API.

Table 7. RESIDUAL STRENGTH OF BALLISTICALLY DAMAGED LAMINATES

Laminate Thickness (in.)*	Spec. I.D.	Projectile Velocity (fps)	Area Gross (in.^{2})	Area Net (in.^{2})	Breaking Load (lb)	σ_g (ksi)	σ_n (ksi)
Aluminum 7049-T73							
0.112	A151	1667	0.301	0.198	16,500	55.0	83.3
0.113	A151	1612	0.301	0.224	17,150	57.2	76.6
0.225	A251	1585	0.601	0.431	30,350	50.6	70.4
0.231	A251	1633	0.600	0.411	27,950	46.6	68.0
0.346	A351	1631	1.497+	0.912	61,000	40.7	66.9
Titanium 6Al-4V							
0.112	T151	1588	0.301	0.186	24,500	81.7	131.7
0.110	T151	1640	0.301	0.209	26,300	87.7	125.8
0.483	T451	1613	2.000	0.810	72,000	36.0	88.9
0.468	T451	1625	1.992	0.770	66,400	33.3	86.2

*Includes nominal 0.005 in. bond line.
+Five-inch gage width.

CONCLUSIONS

Results obtained from this modified program are encouraging relative to the use of metal laminates for ballistically tolerant applications. However, it must be understood that because of the limited scope of the program these results represent only a partial characterization of Al-7049 and Ti-6Al-4V in laminate form. Some of the findings for the 0.050-inch ply laminates are as follows:

1. Fracture toughness of both alloys is independent of laminate thickness for the constant ply thickness of 0.050 inch.

2. Ballistic damage increased as a function of laminate thickness for Al-7049, whereas for Ti-6Al-4V it increased between the two- and four-ply laminates and remained essentially constant thereafter.

3. Residual strength for Al-7049 decreased as a function of laminate thickness, but it is significant to note that all values were above the yield strength of the alloy in the monolithic condition. Additional work is necessary to complete the residual strength phase for both alloys.

4. The net section fracture stress of ballistically damaged Al-7049 laminates exceeded the monolithic yield strength. This was also true for the two-ply laminate of Ti-6Al-4V.

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